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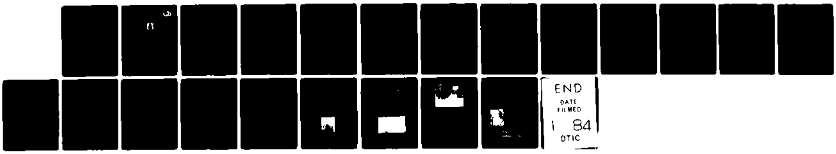

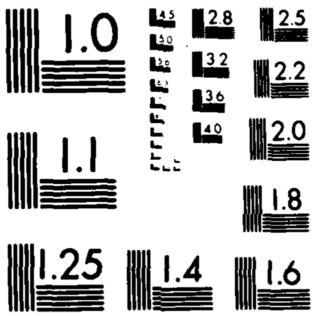

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FOREIGN TECHNOLOGY DIVISION

DEVELOPED ELECTROTECHNOLOGY DURING A "COSMIC FROST"

by

A. Witwicki

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FTD-ID(RS)T-1088-83

EDITED TRANSLATION

FTD-ID(RS)T-1088-83 8 November 1983

MICROFICHE NR: FTD-83-C-001348

DEVELOPED ELECTROTECHNOLOGY DURING A "COSMIC FROST"

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English pages: 18

Source: Horyzonty Techniki, Nr. 8, 1974, pp. 11-13; 22

Country of origin: Poland
Translated by: SCITRAN
F33657-81-D-0263
Requester: FTD/TQTD
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DEVELOPED ELECTROTECHNOLOGY DURING A "COSMIC FROST"

by Andrezej Witwicki

At the beginning of our century a certain Dutch scientific center developed an apparatus for the liquifaction of gases with exceptionally great productivity, by the aid of which it was possible to perform broadly conceived tests with the use of low temperatures. These included the measurement of the resistance (electrical resistance) of various metals at temperatures close to absolute zero. These were, however, tests with a basic character, without any real possiblities for the practical application of their results. But in 1911, something unexpected took place: the measurement of the resistance of lead at constantly low temperatures suddenly diminished--it became equal to zero (HT 7-8/69). Knowledge of this phenomenon, designated as superconductivity, created new possibilities for all fields of technology, connected with the use of electric currents.

The practical application of superconductivity today encompasses the entire range of power of electronic devices--from electronic microsystems, especially logical ones, and precision measurement devices, operated by magnetic fields, to electron microscopes and electromagnets for nuclear devices, as well as for engines, transformers, generators and high power transmission lines.

Unfortunately, hopes for operation with a current of sufficiently high intensity with a diminishing conductor diameter have not been met. Superconductors have their own requirements and the transition of metals and alloys (only a few) from the "normal" state into the superconducting is dependent upon three factors: temperature T, the density of current J and the intensity of the magnetic field B. The point designating the operating conditions of a given material must possess a lower critical value than each of these three factors (ill. 1).

This triple limitation causes many difficulties. A section of the conductor, although much smaller than "normal", must be adapted to the current's intensity. A small magnetic field, existing especially often in electric machines and even with alternating current threatens the superconductor's "degeneration".

But, what about temperature? Numerous laboratories have not stopped searching for the material, for which the critical value of that parameter would be as great as possible. The use of an appropriately low temperature is no longer the real problem, because for example liquid helium does not exceed 4.2 K (-268.8°), and that is completely satisfactory, but at 1 W of power, taken in such a low temperature, the freezing device (for example a helium condensing unit) draws 1 kW of power, and consequently, the freezing efficiency falls to less than .1%.

Together with the decrease in resistance, the dissipation of heat ceases with the flow of electric current, but even the best thermal insulation does not completely stop the discharge of heat into the air, especially with large devices. Therefore, the best way to cool down such materials as pure copper or aluminum to around 70 K--the boiling temperature of liquid nitrogen--has been adapted to this process. Resistance, then, has been lowered a 1000 times; in this same relation, losses in Joule'a-Lenz heat are diminished and the freezing efficiency at 70 K (-200^{o} C) amounts to several percent.

Devices operating on this principle are called cryoresistant, and like superconductors, make possible the use of large current densities, and thanks to this, have small proportions and mass or very great power without changing the overall dimensions. These advantages are balanced out by the need for the use of developed freezing apparatuses. Where it is a question of great power or special applications, the introduction of cryotechnology is unquestionably justified.

In the conditions existing in Poland, an additional argument is the discovery of ample helium sources. Therefore, research in this area has reached a high rank; that is, it is a critical problem in the national economy.

If there are already efficient apparatuses which are operated by liquid gases on an industrial scale, the solving of other problems can be considered: the production and use of superconductive, cryoresistant and insulation materials, of conductors and transmission lines and the design of transformers and electric cryomachines.

SUPERCONDUCTOR MATERIALS

Some pure metals make up superconductors, but in general at very low temperatures, on the order of a fraction of a kelvin, beyond this they have a very small critical value of magnetic induction. Only niobium has found practical use. Alloys and compounds of metals with especially well chosen elements are much better: an alloy of niobium with titanium already has B_{kr}=12 T, and compounds of niobium with vanadium (for ex. Nb_3Sn and V_3Ga) can operate at several kelvins and around 20 Teslas. The record holder among the materials used in the semi-industrial scale is a compound of niobium, germanium and aluminum, whose acceptable temperature value is 21 K, and whose field can reach values of up to 40 T.

Many new compositions with much better parameters appear annually, and a dream of specialists is to discover a material which maintains superconductive properties even at room temperature. It is difficult, however, to dwell on some kind of hope, and the liquid helium method still cannot be dispensed with.

THE CONSTRUCTION OF CONDUCTORS AND CABLES

Electric conductors, besides superconducting wires, must consist of a stabilizer, protecting the superconductor from damage during degeneration.

If some kind of disturbance causes a transition of a section of the circuit into the normal state, the current flowing through with great intensity begins to intensively heat it, all the more so if the superconductor in the normal state has in general a significant resistance (adequate resistance). In order not to allow the fusion or even the vaporization of the superconducting material, it is necessary to secure for the currents something in the way of an average path with a small resistance which allows the by-passing of the degenerated area. The basis of the effectiveness of this protection is defined as partial or total stabilization (ill.2). The most frequently used solution is to set many (up to several thousands) superconducting strands in a joint stabilizing casing (especially for spherical conductors) or to place a thin layer of superconducting material on a wire, tube or band, produced from the stabilizer and serving at the same time as the carrying structure.

Next comes the insulation. It must fulfill a dual role--protecting against an electrical short and an exchange of heat with the surrounding environment. Fluid gases, entering in general into the framework of the thermal shield, fortunately, have good insulation properties, better than even tranformer oil. In order to prevent the exchange of heat through the conductor, insulation as simple as that found in common thermostats is used (especially in instruments with rigid coverings). In cables, which must be elastic, insulation with very thin layers of polyethylene or teflon foil, among which is found a vacuum or fluid gas, is used. The insulation's quality is especially important in energy lines, which must carry high voltage.

Many countries have begun to produce models of such transmission lines, from simple direct current cables (ill. 3) to complex lines for triple phase alternating current (ill. 4), which, because of the magnitude of the proposed solution, can economically compete with conventional lines. On par with superconducting cables are cryoresistant ones. From the point of view of construction and exploitation costs, these are equally advantageous and do not require the use of hard to get materials.

Research into this field has also been performed in Poland. The Institute for Basic Electrotechnology of the Polytechnical University of Wroclaw began to deal with the question of cryoresistant cables in 1971. Research encompassed mainly materials and models of insulation systems. The parameters of a series of elements (especially layered superinsulation of paper--liquid nitrogen) were compared with data provided in the literature. Based on the results obtained, a model of a cable with strands of very pure aluminum, cooled by liquid nitrogen, was constructed. Typically, the main stress was placed on testing the durability of the electrical insulation as a function of time--that is, ageing tests.

CRYOTRANSFORMERS

The construction of cryotransformers is another direction of research carried out within the framework of the knotty problem of the "utilization of cryogenic phenomena in electrotechnology". Work has been concentrated in the Electrotechnical Institute in Warsaw and has an introductory character, preparing materials for the design of future prototypes.

The greatest difficulty in this question is the shortage of superconducting materials, capable of working in a powerful alternating magnetic field. Only with such a superconductor will it be possible to construct a transformer of great power with relatively small dimensions. The need for such a design becomes more burning every day, because leading countries in the field of building large transformers, including Poland, are reaching the limits of technical possibilities. For example, in the Research-Production Center in Lodz, triple phase transformers with a power of 240 MVA and an upper voltage of 260 and 420 kV have been designed and produced. One of the first parameters taken into consideration during designing was the possibility of transporting these units, with the use of special wagons. Poland is building generators with continuously increasing unit power (usually 360 MW), and more powerful units will be necessary for the nuclear power plants of the future. The use of triple phase bock transformers for cooperation with such generators is very advantageous in comparison with separate transformers for each individual phase. For a while progress is still possible, by using new ferromagnetic and insulation materials, as well as by using intensified cooling, but only cryotechnics can radically change the situation.

It is valuable, anyway, to recognize that the utilization on a wide scale of direct current and also the building of superconducting or cryoresistant lines, which operate at low voltage and greater current, can eliminate the need for the use of high voltage transformers.

ELECTRICAL CRYOGENIC MACHINES

Present progress in the field of the production and utilization of electrical energy in machines of great power rests on two factors: size and intensive cooling. Together with everything else, the machine's mass is also increased: modern turbogenerators with a power of 1000 MVA are 10 m long, 5 m wide and weigh aound 850 tons. Larger machines could not be transported. The cooling of standing insulation by water, and runners--by hydrogen under great pressure, is the optimum solution within the framework of conventional technology and it would be difficult to hope for some new discovery here. The next significant factor is the value of the magnetic induction, limited by the saturation state of the ferromagnetic core up to around 2 T.

The possibility of using supeconducting insulation with a permissable current density of 10^9 A/m^2 in a field with an induction of up to 10 T has allowed the core to be eliminated (over half the weight of the machine!), decreasing the insulation's volume and increasing the working value of the induction by 5 times, as well as the power. The perspectives are, therefore, promising, but there are countless difficulties! The problem is in the design and lubrication of the bearings; the construction of the machine's spindle, which must bear great torque with minimal heat conduction; the leading out of the current from the cooling zone; the small density thermal superinsulation, located in the interstice between the runner and stator; spontaneous heating of the refrigerant affected by vibration; the shielding of the coreless machine and the eventual protection of the superconductor from operation during the inadmissable fluctuation of the magnetic induction.

Other qualifications essentially limit the number of possible designs of cryogenic machines. There are primarily two variants: unipolar, direct current machines and alternating current machines with induction superconducting insulation.

DIRECT CURRENT MACHINES

Unipolar machines (the so-called Faraday machine) have been known since 1831. Its simplest version is composed of a metal shield, rotating in a stable magnetic field, created by the induction insulation (ill. 5). The current leading to the shield over two complete sets of sliding contacts--one in the vicinity of the axis, the other on the shield's circumference--flows through it radially, creating a torque compatible with the regulation of the left hand side. When the shield's rotation is constrained SFM is inducted into it and the machine does not operate as a motor, but as a generator of direct current. Until recently, these machines did not find broad application with regard to the real need: very low working voltage (a few volts), and then a greater current intensity delivered by the sliding contacts. The present interest in this type of machine must be ascribed to the utilization of superconductors.

The induction insulation of the unipolar machine operates with direct current and is immobile. The magnetic field, originating from the current flowing in the runner, is perpendicular to the induction field; it does not have, consequently, a reverse or electromagnetic effect, but a mechanical one. It makes possible the operation of superconductors with values close to those of cryogenics, without the fear of exceeding them during load changes or short-circuits.

Research is mainly interested in the improvement of sliding contacts (the typical carbon brushes are disappointing at increased speeds and significantly limit the current's value) and the method of raising the working voltage. Liquid metals are used to bring the current to the machines' rotating elements: mercury and melted sodium or potassium, but these materials are dangerous to use. The best brushes designed were shown to have thin metallized carbon filaments. The increase of outgoing voltage can be obtained, joining several rotating shields in a joint induction field or operating one shield in the radial sections, as well as a broad combination.

The design of the hitherto largest unipolar superconducting motor, built in Great Britain (ill. 6), was based on this last development. Its power amounts to 2.4 MW and its rotary speed is 200 rpm. The induction tube has 4000 coils made from a Nb-Ti alloy and completely stabilized copper and the maximum induction value of the created field amounts to 3.7 T. The shield is two sided, divided into 80 segments, so that the working voltage amounts to 430 V, and the current--5800 A. A similar motor, with a power of 3 MW, finished in Japan, is now undergoing control research.

There exists a possibility that machines with a continuous current with a power of 200 MW (larger energetic turbogenerators operating in Poland have as much power) and an outgoing voltage of 1000 V will be developed in the near future. In relation to conventional generators these have a mass reduced by 90 percent (!) and a bit more than half the cost. Unipolar machines have little inertia and easy rotating speed control. Therefore, it is planned to use them to propel rollers, hoist machines and pumps, as well as ships. This last possibility is especially useful with regard to its limited mass. The building of a motor-generator with a power of around 300 kW was finished in the United States, and an analogous system with a power of 2 MW was finished in Great Britain.

ALTERNATING CURRENT MACHINES

A much greater value of the machine's unit power, necessary from the economic point of view, can be obtained in heteropolar machines, especially in synnchronous generators. The insulation of the armature of such a machine operates with alternating current, therefore, superconductors are used most often in the induction circuit. Since the total electrical power encumbers the armature, it cannot be placed in the rotor, where the transfer of power greater than 100 MVA through the sliding contacts is unrealistic. The induction insulation must be placed in front of this, and therefore, it is necessary that the rotating cryostat—element operates especially at the surrounding temperature. This must also permit the inflow and outflow of liquid helium, which cools the cryostat. The rotor is in general surrounded by an electromagnetic screen of metal with great conductivity and a layer of vacuum insulation (ill. 7).

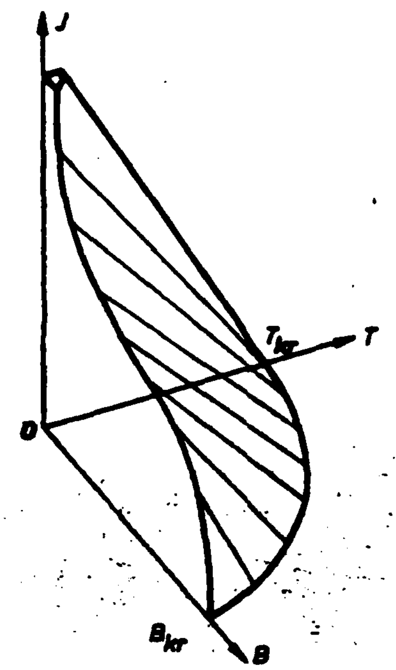
The screen doubly protects the rotor—against the changing of the magnetic field, arising from the current in the stator's insulation, which is dangerous for the superconductor, and against heat radiation. It can be formed from a layer of pure copper or aluminum and placed on the inner surface of the vacuum shield. Also, the shield can be an independent structure, cooled additionally by liquid nitrogen or hydrogen (boiling temperature of about 20 K).

The armature's insulation (in the stator) is conventional copper or aluminum, cooled by oil or water. A design has been developed, which uses cryoresistant insulation.

Larger synchronous machines of this type are built in the Soviet Union (the Leningrad Polytechnical University—1 MVA) and in the United States (the Massachusetts Institute of Technology—2 MVA and the Westinghouse Electric Company—5 MVA), however, the difficulties met with have forced basic research to be expanded to include the component elements of these devices. Several countries, including Poland, have researched and constructed smaller experimental prototypes.

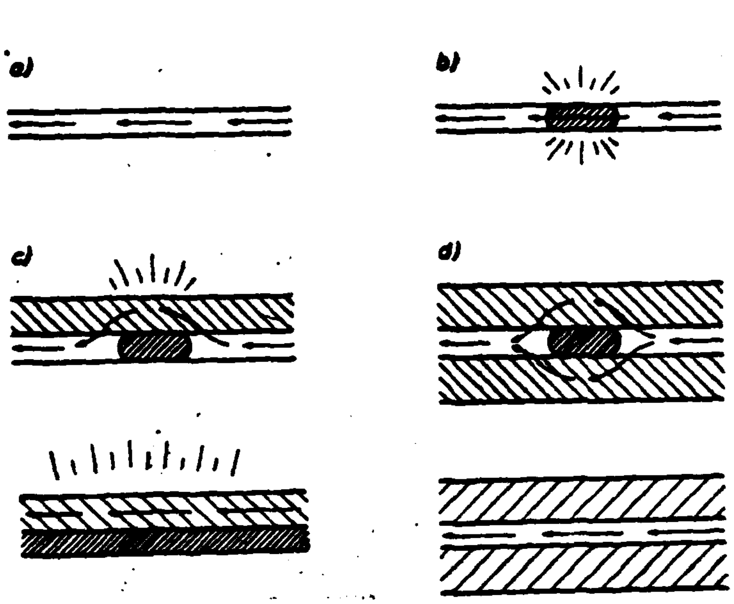
The specifics of the projected elements of machines, which operate in extremely low temperatures, require the linking up of theoretical and practical information from many fields. Therefore, the Lower Silesian Electrical Machine Factory, "Dolmel", in Wroclaw has begun work aimed at both the solution of certain technical problems, as well as the training of expert cadres, occupied with cryotechnical applications. The mechanical properties of various materials, anticipated for the the constructon of prototypes, are being studied. Moreover, a cooling system, based on helium gas is being designed; the maintenance of temperatures at around 5 K require an unusually precise measurement-regulation system for the rotating cryostat. The design of a special head, which permits the bringing of electrical current and refrigerant to the rotor, is already finished.

The Wroclaw research center is in close contact with a team of designers in the GDR, who are working on the same subject. Our neighbors have already developed their own prototype with a power of 20 kW, and cooperation between both groups will hasten the tempo of further work. It is, therefore, quite probable that a Polish cryogenic machine also will be in operation in the course of the next few years.

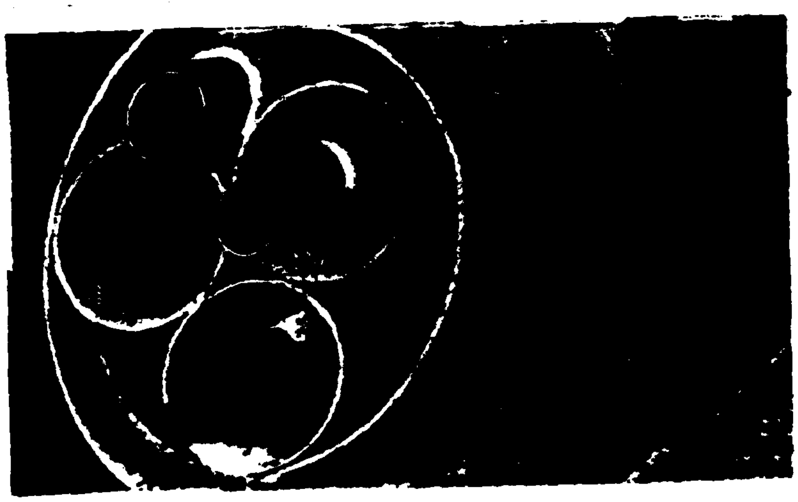


Ill. 1 The boundary surface of the superconductive state for the so-called Type I superconductor (generally pure metals). The boundary of the Type II superconductor is not so sharp; a certain transition area exists.

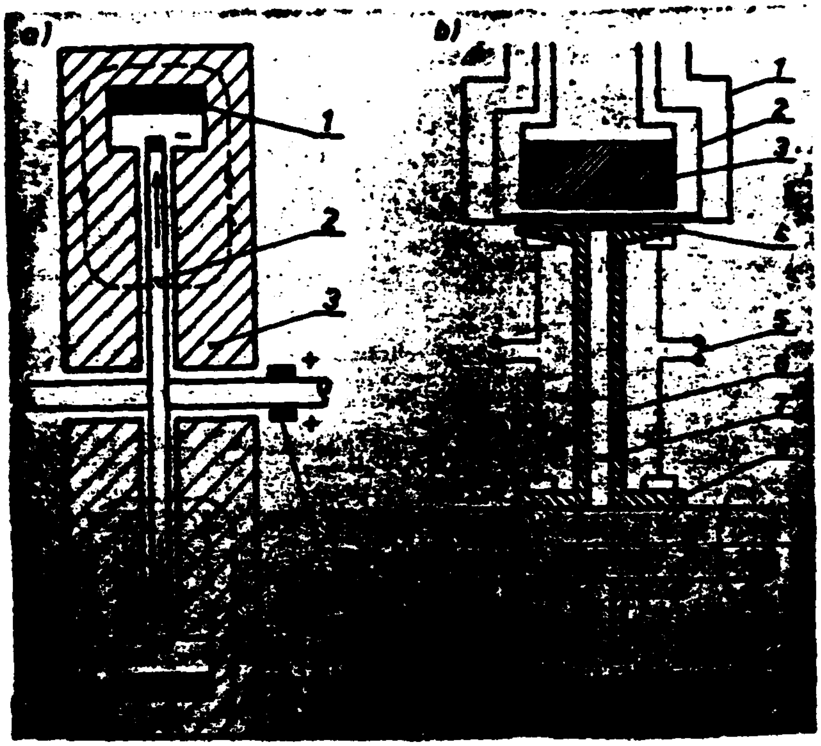
Ill. 3 The simplest design of a superconducting direct current cable: 1-the heat superinsulation, 2-copper or aluminum pipe, 3-superconducting layer



Ill. 2 The superconductor's stabilization. The superconducting conductor's local degeneration (a) causes the discharge in it of a great deal of heat (b). the partial stabilization by low resistance material--copper or aluminum--secures the easy transition to the normal state (c), the entire stabilization allows the return to the superconducting state after the disturbances withdraw (d)



Ill. 4 A model of a triple phase cable. Three pairs of concentrated pipes corresponding to the three phases together with the pipes, which return the liquid helium to the cooler, are situated in a vacuum in a joint housing.



Ill. 5 A unipolar machine: a) conventional: 1-induction insulation, 2-Faraday shield, 3-ferromagnetic core, 4-current conducting brushes: b) superconductors with a two-sided shield: 1-the cryostat's external housing, 2-thermal shield, 3-superconducting inductive insulation, 4-external glide ring, 5-outlet of the runner's circuit, 6-shield creating the runner's insulation, 7-insulation between the shields, 8-internal glide ring

Ill 6. The shield of a unipolar motor with a power of 2.4 MW. The inner slide rings and one segment of the outer ring are visible. The shield's diameter is 235 cm

Ill. 7 A sketch of a synchronous machine with a superconducting induction circuit in the rotor: 1. the outer ferromagnetic (residual core) or non-magnetic screen; 2. the conventional or cryoresistant insulation of the armature; 3. the immobile vacuum shield; 4. the vacuum gasket; 5. bearing; 6. vacuum; 7. superconducting induction insulation; 8. electrothermal screen; 9. the rotor carrying structure